Flow over Difficulty Bathymetry: Processes and Parameterizations

Michael C. Gregg, Chair
Applied Physics Laboratory
University of Washington, Seattle, WA 98105
Phone: (206) 543-1353 fax: (206) 543-6785 email: gregg@apl.washington.edu
and
Parker MacCready, Scholar
School of Oceanography
University of Washington, Seattle, WA 98195-5351
Phone: (206) 685-9588 fax: (206) 543-6073 email: parker@ocean.washington.edu

Award # N00014-97-1-1053
http://www.apl.washington.edu
http://www.ocean.washington.edu/people/faculty/parker/

LONG-TERM GOALS

The long-term goal of this work is to develop a physical understanding of oceanic flow along irregular, sloping, coastal topography and to quantify and parameterize, if possible, the mixing these flows produce. To model the coastal ocean effectively, it is essential that we understand how flow over rough topography affects boundary drag. By understanding the basic processes of internal wave generation and flow separation we will be able to predict the effects of unresolved bathymetric roughness in numerical simulations.

OBJECTIVES

Objectives are 1) to synthesize emerging measurements and numerical simulations of flow and mixing over rough topography to assess their global importance, 2) to understand the physics controlling exchanges of momentum, heat, and salt between boundary layers over continental slopes and the ocean's interior, 3) to use laboratory and numerical results to design experiments to illuminate crucial aspects of flow and mixing over rough topography, and 4) to develop observational and numerical methods which allow us to characterize and predict the flow disturbances caused by rough topography.

APPROACH

To relate intense mixing being observed by flows over rough topography, Dr. Gregg's group identified the need for in-situ shear measurements and designed an addition to their depth-cycling towed body to add upward and downward Acoustic Doppler Current Profilers (ADCPs). ONR separately funded this addition and its use on the Nearfield phase of the Hawaii Ocean Mixing Experiment (HOME). This group in cooperation with Matthew Alford (1999-2000 postdoc on this grant) has also been analyzing data from the Acoustic Current Meter (ACM) carried on MMP3, a loosely-tethered profiler. The group participated in the survey phase of HOME to investigate and quantify mixing and internal tides generated by barotropic tides flowing over the Hawaiian Ridge. They have also been working with Mark Stacey, UC Berkeley, to quantify the budget of turbulent kinetic energy from the Suisun Cutoff Experiment of 1999.

Dr. MacCready's group uses a suite of approaches: 3-D numerical simulations, field observations, analytical theory, and lab experiments. These are all focused on the basic configuration of stratified flow past a ridge on a slope. Tidal and rotational effects are included as well. The numerical simulation is done using the Hallberg Isopycnic Model (HIM) and the Region Ocean Modeling System (ROMS). They have completed three years of field work in the Strait of Juan de Fuca, collaborating with Chris Garrett and Richard Dewey at the University of Victoria. This data is being analyzed by Wayne Martin (graduate student). Their current field program (funded by NSF) now focuses on a sharp headland in Puget Sound, Three Tree Point. Kate Edwards (postdoc) works on data analysis in both locations. Ryan McCabe (graduate student) works on the Three Tree Point observations and on related, idealized, lab experiments.

WORK COMPLETED

Matthew Alford published two papers in Journal of Physical Oceanography. In the first (Alford 2001a), he used NCEP/NCAR atmospheric model winds, validated with bouys, to compute the global distribution of energy flux from the wind to near-inertial motions. This impacts the issue of global energy budget for mixing, since the total (0.3 x 10^12 W) is comparable to the input from conversion of barotropic tidal energy near strong topography. In another (Alford 2001b), he investigated the kinematic interactions between the internal tide and near-inertial phase lines, showing that the tide vertically heaves the near-inertial wave, leading to a clear example of frequency smearing by the so-called "fine-structure contamination." Dr. MacCready and Dr. Geno Pawlak (1998-99 postdoc on this grant) completed two papers on their initial numerical simulations and lab experiments. MacCready also wrote two papers on a novel way of analyzing isopycnal mass balances in an S-coordinate model. Wayne Martin analyzed the Juan de Fuca observations for their tidal, boundary layer, and internal wave characteristics. Kate Edwards participated in a cruise of the R/V Thompson at Three Tree Point with Jim Moum of Oregon State University. Dr. Edwards is analyzing a substantial microstructure dataset from there, to calculate both frictional stress and the baroclinic part of form stress across the ridge. They participated in a subsequent cruise at Three Tree Point, mainly using GPS drifters and repeated ship-mounted ADCP surveys.

RESULTS

Major new results came from the HOME experiment for which Dr. Gregg was partially supported by the Chair. Figures 1 and 2 below show strong mixing emanating from the Kaena Point ridge, off the NW coast of Oahu. The elevated mixing appears to lie along characteristics rising from the ridge, much like the mixing along a beam of the internal tide off California reported by Lien and Gregg (2001).

Dr. MacCready's group found that pressure drag on stratified flow past a ridge can be due to either internal wave generation, or horizontal flow separation (which forms a headland eddy). Using linear wave theory, they found that the transition from horizontal flow around the ridge to more vertical, wave-like flow over the ridge may be predicted to occur when $U/(LN \sin a) = 1/2$ (faster flow is wavelike) where U is the speed of the along-slope flow, L is the along-slope length of the ridge, N is the buoyancy frequency, and the slope angle is a. Remarkably, this predictive criterion proved useful even for numerical simulations with large ridge height and realistic mixing and boundary layer parameterizations (Fig. 3).

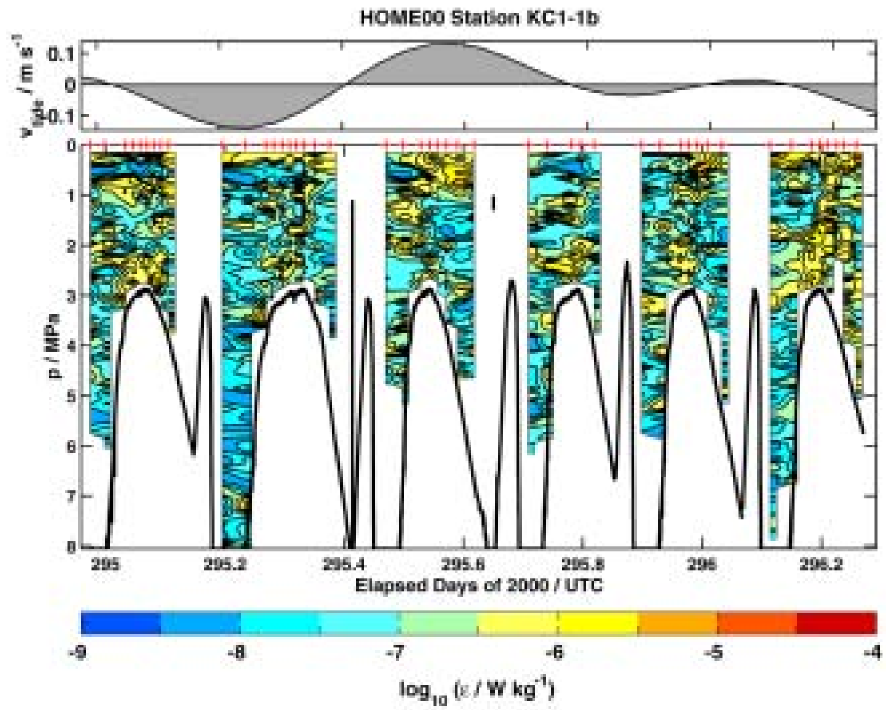

Fig. 1. Mixing over Kaena Pt. ridge during neap tide, from HOME Survey Phase in October 2000.

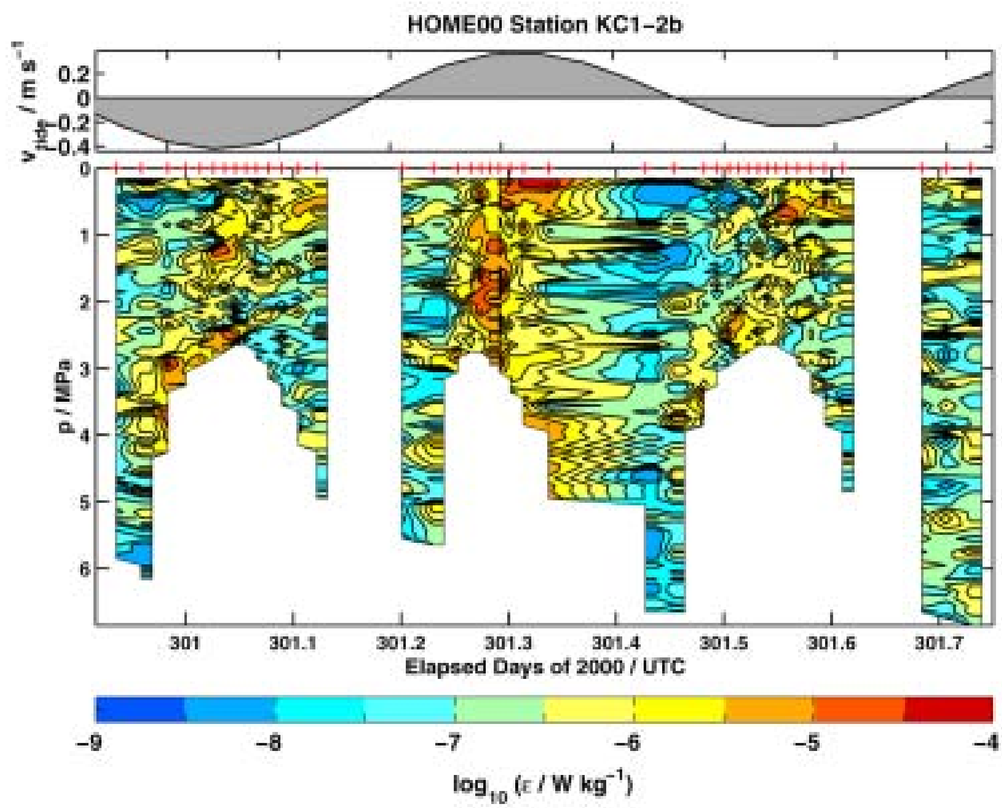

Fig. 2 Mixing over Kaena Pt. ridge during spring tide.

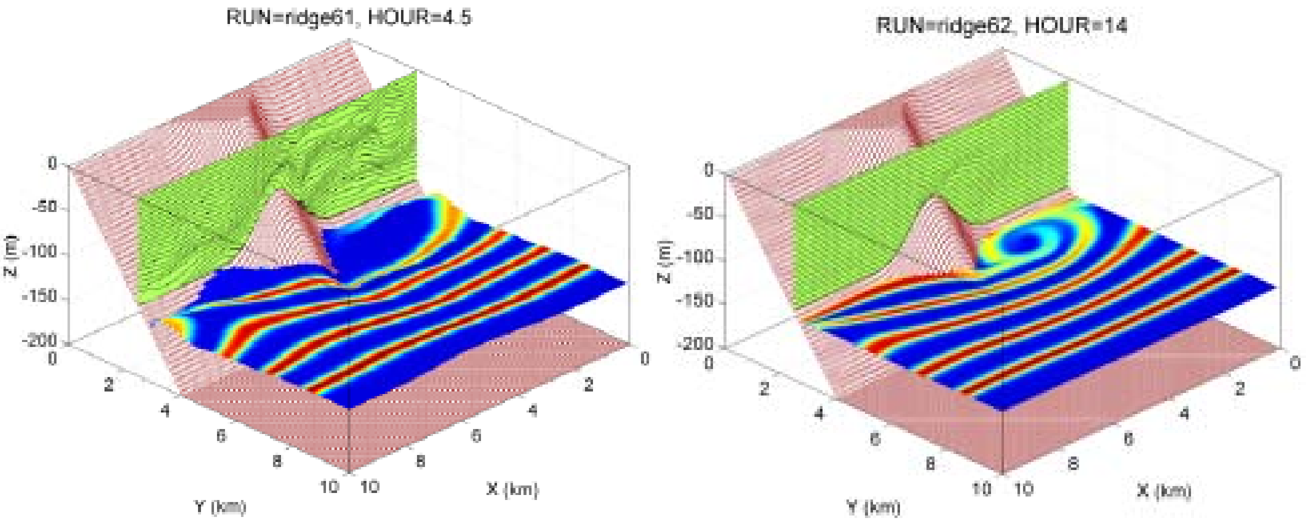

Figure 3. Results from a 40-layer numerical simulation of re-entrant channel flow past a ridge on a slope (slope angle = 1/20). Isopycnal displacements are shown in the vertical plane and tracer stripes are shown on an isopycnal. The run shown in the left panel is forced with a 0.5 m s^{-1} flow from left to right, and strong lee wave generation is observed, consistent with the analytical predictions. If instead (right panel) we force with a slower flow, 0.125 m s^{-1}, which is below the low-speed cutoff for wave generation, no waves are formed. Instead, a coherent horizontal eddy develops in the wake due to flow separation. The pressure drag coefficient on the ridge is approximately the same in both these cases, despite the different physical mechanisms.

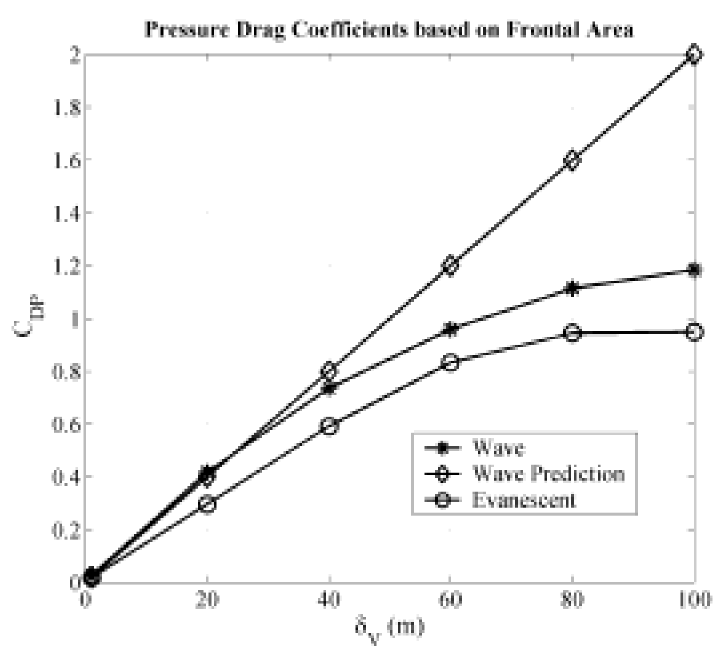

Figure 4. Mean drag coefficients for all the ridge numerical simulations, plotted versus vertical ridge height. Experiments in the wave-generating regime are plotted as stars, while those in the slow flow regime are plotted with circles. Our analytical prediction of the drag coefficient is plotted with diamonds. Ridges in both regimes can have large drag coefficients, leveling off to about 1 as the ridge size increases. The wave generating case matches the prediction well for small ridges.

They calculated the pressure drag on the ridge that may be due to either internal wave generation or horizontal separated flow. In both cases, an extremely simple result emerged. The coefficient of pressure drag, referenced to the projected frontal area of the ridge, was approximately 1 for all large ridges (Fig. 4). In these cases, the pressure drag on the ridge was about 5 times greater than the frictional drag.

The idealized modeling made it clear that vortex generation from sloping ridges could be an important process, both as the expression of pressure drag and as a coherent flow structure in itself. However, vortex dynamics near complex bathymetry have been little-studied. With 3-D numerical simulations of tidal flow at Three Tree Point, the group found that a vortical eddy was formed during each flood or ebb tide. The eddy extended through the full 200 m water depth, and its core followed the ridge crest slope (slope = 1:5, vertical:horizontal). It is apparent that the vorticity signature of the eddy extends throughout the water column, and is fairly distorted by horizontal flows near the surface. In addition the eddy from the previous ebb shows that the eddy vorticity only survives at this level near the surface, and is apparently destroyed in some way deeper down.

Analysis of vorticity from drifter releases (August 2001) at Three Tree Point shows the eddies decay over less than 18 hours, whereas simple scaling of their spindown by bottom friction suggests that they would survive at least 46 hours. The numerical simulation suggests a reason for this apparent contradiction: the eddies may be strongly sheared by interaction with neighboring eddies, leading to their rapid dissipation.

IMPACT/APPLICATION

Together with earlier observations off California, Gregg's observations over Keana Point Ridge show that tidally-generated mixing is very important in many coastal and island locations. Because this mixing occurs in stratified water and is very intense, its effects must be incorporated in mixing parameterizations before numerical models can accurately predict dynamics over continental slopes and ridges.

The most important future impact of Dr. MacCready's work will come through the development of a parameterization of sub-grid-scale pressure drag based upon the pressure drag coefficient presented in Fig. 4. We plan a series of numerical simulations in the final year of the grant to do this.

TRANSITIONS

Our analytical prediction for the transition from wave to eddy regimes, modified to include the effects of Earth's rotation, are being used by Eric Kunze and Jon Nash (UW) in their interpretation of data from the TWIST experiment.

RELATED PROJECTS

Sonya Legg (WHOI) is doing numerical modeling of the TWIST region. Her work focuses on internal wave generation on a corrugated slope due to barotropic cross-slope flow, whereas ours focuses on motions forced by along-slope flow. Jim Moum (OSU) made microstructure measurements at Three Tree Point in March 2001, and has proposed to (NSF) to do further work there, coordinating with our 2002 cruises.

REFERENCES

Lien, R-C. and M. Gregg (2001), Observations of turbulence in a tidal beam and across a coastal ridge, *J. Geophys. Res*, 106, 4575-4591.

PUBLICATIONS

Alford, M. (2001a), Internal swell generation: The spatial distribution of energy flux from the wind to mixed layer near-inertial motions. *J. Phys. Oceanogr.*, 31, 2359-2368.

Alford, M. (2001b), Fine-structure contamination: observations and a model of a simple two-wave case. *J. Phys. Oceanogr.*, 31, 2645-2649

Gregg, M.C. (2000), Turbulent mixing in the ocean. In A. Zatsepin and A.G. Ostrovskii, ed., *Oceanic Fronts and Related Phenomena: Konstantin Fedorov International Symposium*, number 159 in Workshop Report Series, pages 181-185. Intergovernmental Oceanographic Commission, UNESCO.

Gregg, M.C. and E. Ozsoy (2001), Flow, water mass changes and hydraulics in the Bosphorus. *J. Geophys. Res.*, in press.

MacCready, P. and G. Pawlak (2001), Stratified Flow along a Rough Slope: Separation Drag and Wave Drag. *J. Phys. Oceanogr.*, **31**, 2824-2839.

MacCready, P. and W. R. Geyer (2001), Estuarine Salt Flux Through an Isohaline Surface. *J. Geophys. Res.*, **106**, 11629-11637.

MacCready, P., R. D. Hetland, and W. R. Geyer (2001), Long-Term Isohaline Salt Balance in an Estuary. Submitted to *Continental Shelf Res.*, in press.

Pawlak, G. and P. MacCready (2001), Oscillatory flow across an irregular boundary. *J. Geophys. Res..*, in press.

Winkel, D.P., M.C. Gregg, and T.B. Sanford (2001), Patterns of shear and turbulence across the Florida Current. *J. Phys. Oceanogr.*, submitted.